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(NASA-CR-116588) LUNAR SOIL MECHANICS
(Bellcomm, Inc.) 22 p

FF No. 602(A)
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CR-116588
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LUNAR SOIL MECHANICS

January 13, 1964

Bellcomm, Inc.
Washington, D. C.

By N. W. Hinners

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SUMMARY

In Part A, a brief survey of soil mechanics is presented with emphasis placed on those aspects directly pertinent to lunar soil mechanics, particularly as concerns measurement of "soil constants," extrapolation of measured properties, and construction of "simulated" lunar soils or models thereof. It is concluded that:

(a) Soil systems react in a complicated manner to testing. Their mechanical properties are aggregate in nature, depending upon a myriad of variables, and are relatively unpredictable a priori.

(b) Once a particular soil has been examined and tested, semi-empirical equations can be used to extrapolate certain properties, including shear strength and bearing capacity.

(c) Theory and speculation indicate that lunar soils, all else being equal, may have more strength than terrestrial soils. There is no evidence that all else is equal.

(d) Calculated values of soil constants, based on extremely simplified and unrealistic models, are not reliable and can be used only to give extreme limits which cannot be used for engineering design purposes.

In Part B, the simulation and testing of lunar soils are discussed as are present and follow-on Surveyor experiments and spacecraft tests which could aid in classifying the lunar surface soil characteristics. Conclusions reached are:

(a) As far as Apollo is concerned, laboratory simulation of so-called lunar soils and the testing thereof is relatively wasteful of time, effort, and money. The simulation is so crude and there are so many unknown variables involved in determining the mechanical behavior and physical make-up of soils that it would be extremely fortuitous if a realistic model were ever made. No engineering design can be based on the behavior of simulated lunar soils and it is doubtful whether further terrestrial testing of such soils as has been done will aid much in the interpretation of Surveyor experiments.

(b) Surveyor and related lunar experiments hold the best hope for determining lunar soil characteristics. Accelerometer experiments and/or soil mechanics tests from a roving vehicle should be capable of large area sampling and allow terrestrial observers to arrive at a confident judgment as to the type of and degree of homogeneity of the lunar surface.

(c) On account of the difficulty involved in understanding and predicting the behavior of spacecraft landing systems, it is desirable to undertake an active program of static and dynamic testing of Surveyor and LEM landing systems. The aim of this is to establish empirical correlation and scaling relationships between the two systems. In turn, this may eliminate much of the need to rely upon soil scaling laws which demand relatively precise knowledge of soil "constants" and which do not allow for differences in landing dynamics between the Surveyor and LEM systems.

PART A: SOIL MECHANICS

I. INTRODUCTION

The nature of the lunar soil is of paramount interest to those people engaged in engineering aspects of Apollo. The main engineering requirement is that we make estimates or measurements of certain properties of lunar soil, including bearing strength, density (porosity), angle of repose, internal friction and response to dynamic effects. In the absence of data we must rely upon making estimates of lunar soil properties based on terrestrial analogy and upon consideration of known lunar processes. It is the purpose of this report to review and evaluate those estimates and pertinent information concerning terrestrial and lunar soil mechanics. Trafficability considerations are not included as such, although much of this report is applicable to lunar vehicle studies.

II. GENERAL

Soil engineers usually classify soils into two major groupings[1]: cohesionless and cohesive. Cohesionless (non-cohesive, granular) soils are those whose engineering characteristics are determined by bulk or gravitational forces. This type of terrestrial soil is composed mostly of particles larger than 1-2 microns diameter. Cohesive soils, made up predominantly of colloidal-size particles, less than 1-2 microns diameter, are those soils whose engineering characteristics are determined mainly by surface properties (although they usually exhibit some granular properties). Terrestrial cohesive soils practically always contain water. When "dry" their properties change although even a "dry" terrestrial cohesive soil is not water-free since its particles still contain layers (1-2?) of tightly adsorbed water molecules.

III. BEARING CAPACITY AND SHEAR STRENGTH OF SOILS

The bearing capacity of a soil is a somewhat arbitrary quantity. This fact necessitates, then, defining the term. In the usage of Terzaghi and Peck,[2] the bearing capacity of a soil is that load per unit area at which the load per unit area (abscissa) vs settlement (ordinate) curve becomes vertical

(Fig 1, curve C_1). In the case where the settlement curve does not become vertical (commonly for "loose" or "soft" soils), the bearing capacity is taken as the load per unit area at which the settlement curve becomes steep and straight (Fig. 1, curve C_2). In essence, that point is reached when the soil undergoes shear failure and is subject to calculation. A mathematical treatment of such failure can be found in Scott[1] and Terzaghi and Peck,[2] the former being a more comprehensive analysis. Only the pertinent results and limitations will be presented here.

The bearing capacity of a circular footing can be approximately represented by:

$$q = 1.3\ c\ (N_c) + 0.6\ \gamma\ r\ (N_\gamma) + \gamma h\ (N_q) \qquad (1)$$

where q = bearing capacity per unit area
c = cohesion per unit area
γ = unit weight of soil
h = depth of footing
r = footing radius

N_c, N_γ, N_q } Bearing capacity factors which are functions of ϕ, the angle of internal friction, and which can be computed on the basis of plastic deformation theory.

For shallow footings the third term on the right is usually ignored and (1) reduces to:

$$q = 1.3\ c\ (N_c) + 0.6\ \gamma\ r\ (N_\gamma) \qquad (2)$$

For cohesionless ($c = 0$) soil (2) further reduces to:

$$q = 0.6\ \gamma\ r\ (N_\gamma) \qquad (3)$$

while for purely cohesive soil (2) becomes, since $N_\gamma = 0$ when $\phi = 0$

$$q = 1.3\ c\ (N_c) \qquad (4)$$

From equations (3) and (4) it can readily be seen that the bearing capacity of a cohesive soil is independent of the footing radius while that of a cohesionless soil depends directly on the footing radius.

Any computation of bearing capacity depends upon knowing c, ϕ, γ, and the bearing capacity parameters as functions of ϕ. The cohesion (capacity to resist shear stresses) and angle of internal friction can be determined by

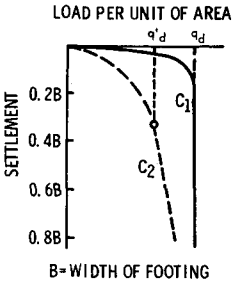

FIG. 1 RELATION BETWEEN INTENSITY OF LOAD AND SETTLEMENT OF A FOOTING ON (C_1) DENSE OR STIFF AND (C_2) LOOSE OR SOFT SOIL (AFTER TERZAGHI AND PECK[2])

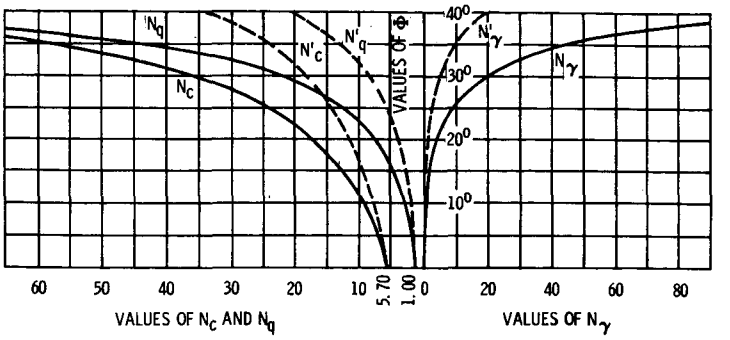

FIG. 2 CHART SHOWING RELATION BETWEEN Φ AND THE BEARING CAPACITY FACTORS (AFTER TERZAGHI AND PECK[2])

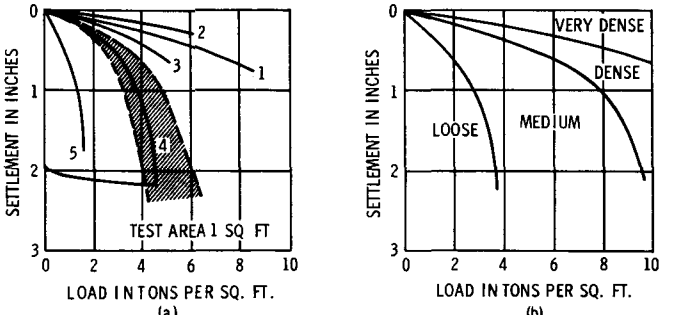

FIG. 3 SETTLEMENT CURVES FOR SAND (AFTER TERZAGHI AND PECK[2])

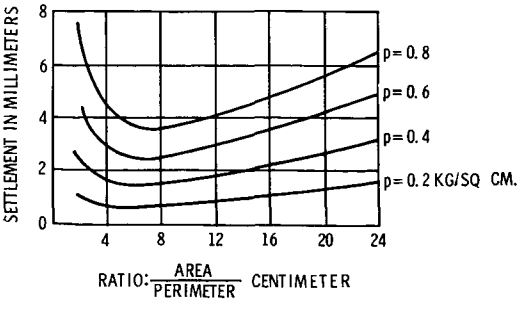

FIG. 4a SINKAGE IN SAND AS A FUNCTION OF LOADED AREA (AFTER KÖGLER IN BEKKER[28])

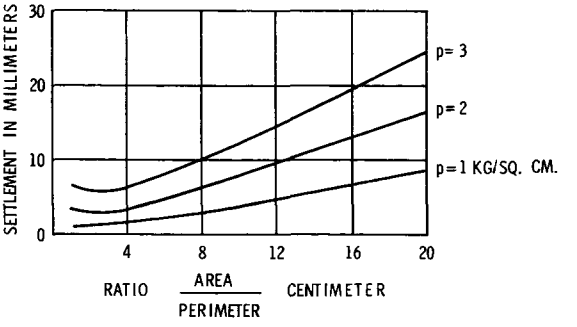

FIG. 4b SINKAGE IN CLAY AS A FUNCTION OF LOADED AREA (AFTER KÖGLER IN BEKKER[28])

simple shear strength tests. The shear strength of a soil can be represented by

$$s = c + p \tan \phi \qquad (5)$$

where p is the normal pressure. A plot of shear strength vs normal pressure yields a curve of slope tan ϕ and intercept c. γ is most easily determined by weighing a unit volume of soil but it can be calculated if the porosity and material density are known. Figure 2 shows calculated values of the bearing capacity parameters as a function of ϕ. The solid lines correspond to parameters applicable to soils having settlement curves similar to C_1 in Figure 1 (general shear failure). If the soil settles as shown by C_2 (local shear failure), then the broken line values are applicable. Those values are only approximate and are based on the assumption, for which there is some empirical evidence, that the cohesion and internal angle of friction for the loose soil are 2/3 the value of a corresponding dense soil. At values of ϕ up to about 20° the differences are not great but above 20° the differences are significantly large, becoming extreme above ϕ = 35°. Whether or not such curves are applicable to extremely porous soils is a moot question. In addition, all calculated values are based on the assumption of semi-infinite media. Scott[1] notes that the problem of estimating the bearing capacity of granular material overlying a rigid base is unsolved.

Sinkage of a footing will occur before the bearing capacity is reached. The amount of sinkage is a function, among other things, of the relative density of a soil, $\frac{e_{max}-e}{e_{max}-e_{min}}$ where $e = \frac{\text{volume voids}}{\text{volume solids}}$ and also of the footing width or radius.

Figure 3 shows the settlement of a plate (area = 1 square foot) on terrestrial sands of various densities. The usual settlement for pressures up to several atmospheres is only one to two inches. It is quite obvious that the less dense the sand the steeper the settlement curve and the lower the bearing capacity. For an extremely porous material the bearing capacity is reached at very small loads and for all practical purposes a bearing strength number, per se, has only academic meaning. This fact has led to corruption of the term "bearing strength" to the point where many people who now refer to the bearing strength under a certain load are, in actuality, referring to a point on the settlement curve. In general, knowing the bearing capacity does not enable one to predict the exact shape of the settlement curve.

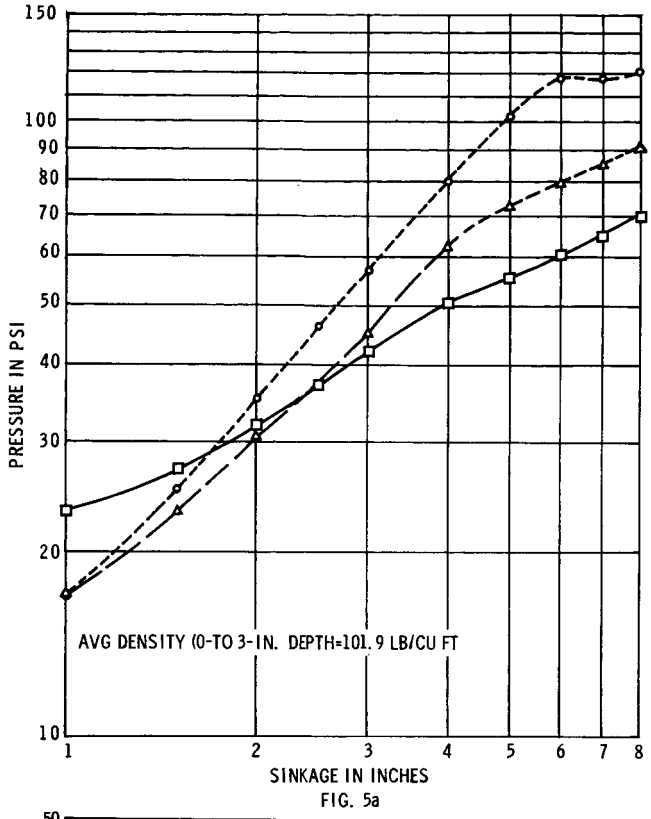

FIG. 5a

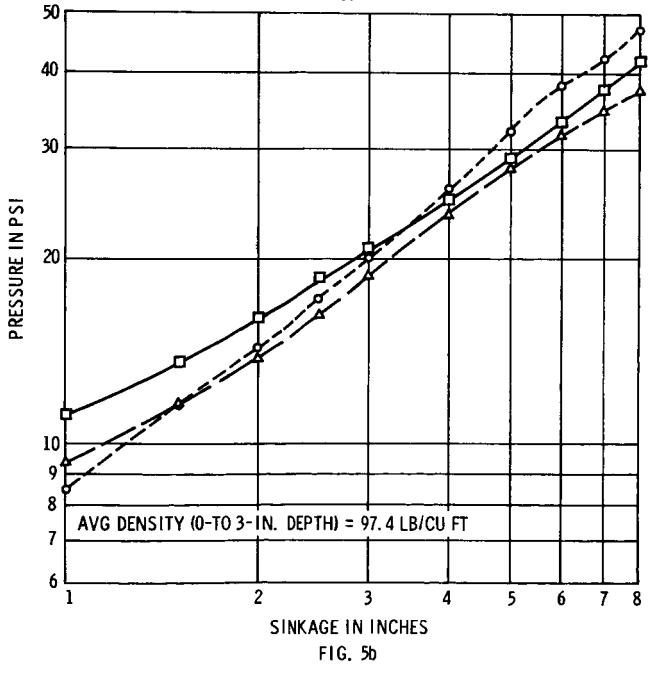

FIG. 5b

LEGEND

1.4 IN DIAM PLATE

2.8 IN DIAM PLATE

4.2 IN DIAM PLATE

PROPERTIES OF THE SAND ARE: C=0 $\Phi = 33^0\text{-}36^0$

FIGURES 5 (a-b): RESULTS OF BEVAMETER SINKAGE TESTS FOR SAND
(AFTER WISMER AND SMITH[6])

In foundation engineering practice, large area (A = 1 square foot) loading plates are used for soil settlement and bearing capacity testing.[2] The purpose of this is to approximate as nearly as possible the real situation since the nearer to the real case, the more reliable is the extrapolation. The effect of the ratio of area to perimeter of footings on sinkage is shown in Figures 4a and 4b. The particular shape of the curves is caused by the combined effect of separate factors operating in opposite directions. On cohesionless soil, for example, as footing width or diameter increases (i.e. area: perimeter increases) the vertical zone of soil subject to compression increases but so does the bearing capacity. In practice the overall effect is often determined empirically and normalizing factors are then assigned to the different scale loading plates used.[3]

IV. BEVAMETER

The bevameter is an instrument used primarily to determine certain soil characteristics which are important in trafficability studies.[4] Part of the instrument consists of a spudded shear ring used to determine c and ϕ while the rest consists of two sinkage plates of different sizes. Successive load-sinkage tests are made with the plates and results plotted as log P (pressure) vs log Z (sinkage). Ideally, two parallel lines result. With the aid of the plot, the coefficients of the semi-empirical vertical stress-strain equation (6) can be determined.

$$P = \left(\frac{k_c}{r} + k_\phi\right) Z^n \qquad (6)$$

P = vertical pressure (psi)
Z = vertical sinkage (inches)
r = width of rectangular plate or radius of circular plate
k_c = "cohesive modulus" ($lb/inch^{n+1}$)
k_ϕ = "frictional modulus" ($lb/inch^{n+2}$)
n = coefficient of sinkage

The modulae and coefficient, which are not related to bearing capacity factors of equation (1), are usually evaluated at a sinkage depth of 1.0 inches although penetration reaches as much as 3 to 4 inches in the usual laboratory tests. That limit is set by apparent bottom effects which come into play when the sample depth is about 3 to 4 times penetration depth. Any experimental program involving scaling must take the penetration depth to soil depth ratio into account (see discussion by Hicks[5]).

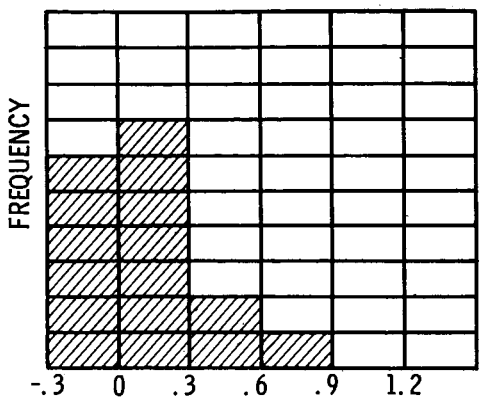

FIG. 6a : "k_c"

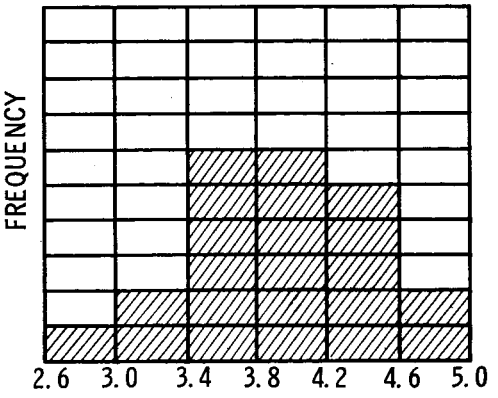

FIG. 6b : "k_ϕ"

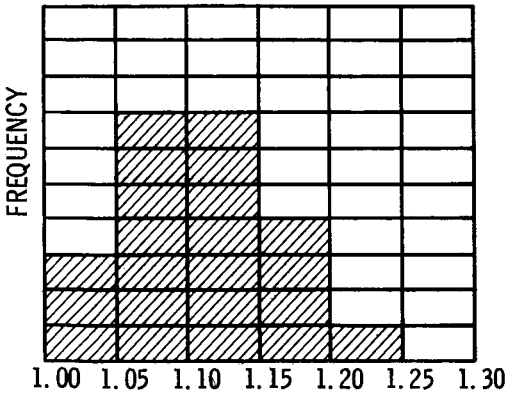

FIG. 6c : "n"

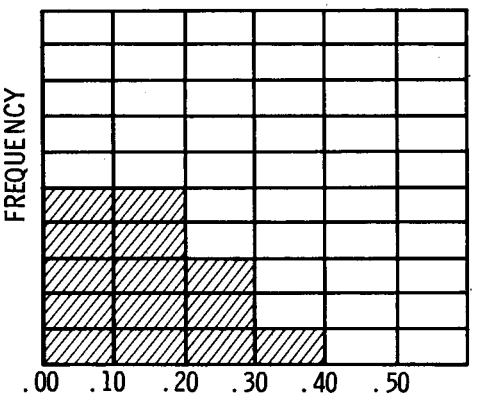

FIG. 6d : "c"

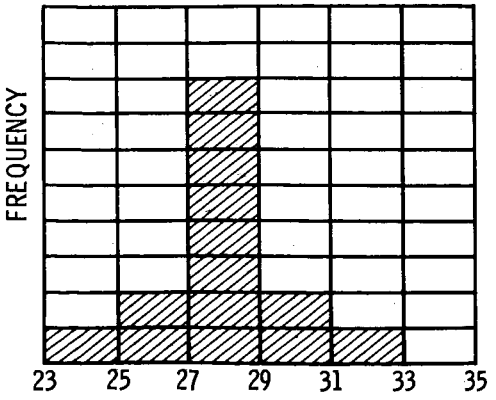

FIG. 6e : "ϕ"

FIGURES 6 (a-e) HISTOGRAMS FOR SOIL CONSTANTS OBTAINED BY BEVAMETER TESTS ON DRY SAND.
(AFTER PAVLICS [7])

By inspection of equation (6) it can be seen that increasing sinkage should be coupled with increasing pressure. In practice this is not always so. If the soil fails as shown by curve C_1 of Figure 1, a constant load would result on continuous sinkage.

For many soils the "constants" k_c, k_ϕ, and n are not constant but are strong functions of plate area and sinkage. The pressure-sinkage curves (log - log) are often not straight and not parallel, resulting in cross-over as shown in Figures 5a and 5b. (Wismer and Smith in discussion of paper by Janosi[6]). Apparently, the equation fits best for lighter (less dense) soils. Harrison (see reference 23, discussion) states that he has had to fit up to three sets of constants in the pressure range from 1 to 10 psi and that it is not proper to fit the points to one equation throughout the pressure range.

Bevameter tests should be evaluated statistically. Figures 6 (a-e) indicate the range of soil values found by Pavlics[7] for a dry sand in controlled laboratory tests. Along with n, k_c, and k_ϕ, the cohesion, c, and angle of internal friction, ϕ, are shown. If equation (6) is maximized and minimized by using the appropriate extreme soil constants found by Pavlics, the following results are obtained (r = 3in.):

P = 1 psi	Z max = 0.48 inches
	Z min = 0.19 inches
P = 10 psi	Z max = 4.8 inches
	Z min = 1.2 inches

It can be seen that if results of any one bevameter test are used to calculate sinkage in this particular sand, the absolute error at low bearing pressures would be small, but at high bearing pressure it could be large and extremely significant. It must be remembered that the range of values used were obtained in laboratory tests. Field tests would undoubtedly result in greater scatter of results.

V. DIFFERENCES TO BE EXPECTED BETWEEN LUNAR AND TERRESTRIAL SOILS

The behavior of lunar soils would be expected to differ from that of terrestrial soils on account of two prime factors: composition and environment. We are interested in how these factors will affect soil constants such as cohesion, angle of internal friction, and porosity, which in turn determine the bearing capacity and sinkage.

A. Composition

Composition is a particularly important factor for terrestrial cohesive soils since the small particles are almost invariably composed of platey clay minerals with a large surface to volume ratio. In addition, the specific clay mineral is important in determining the soil properties because the various clays react differently with the water and its dissolved salts. It is not expected that clay minerals will be present in lunar soils since clays are products of weathering in hydrous environments which are absent (at least now) on the moon. Lunar soils, both cohesionless and cohesive, would probably be composed of non-hydrous silicate minerals. It is quite possible that some metals and/or metal oxides would also be present.[13]

B. Environment

(1) Gravity: The lower lunar gravity could conceivably cause the angle of repose and porosity of lunar soils to be different from that of terrestrial soils. Calculations by Halajian[8] indicate that gravity has essentially no effect upon the angle of repose of cohesionless soils but that a given cohesive soil in a lower gravity field would have a steeper angle of repose and might have a higher porosity if cohesive forces are large enough.

There is no obvious reason why the surficial porosity of a freshly accreted cohesionless soil would differ in various g environments unless the velocity of accreting particles became significant in causing grain readjustment and packing. However, as noted by Ryan[9], the rate of porosity decrease with depth due to compaction under the weight of overburden would be less for a soil in a lower g environment.

Halajian has noted, after inspection of the bearing capacity equation, that in a given compact, cohesionless soil, a given object should sink the same amount on the moon as on the earth. On the other hand, if the cohesionless soil is extremely loose and acts as a shock absorber, sinkage of a given object would be scaled as the ratio of the gravity fields.

(2) Vacuum: The effect of the lunar vacuum on certain properties is predictable as to direction but not as to degree. No doubt a mineral surface, cleaned of lubricating moisture and gases, will have a higher coefficient of static friction than a contaminated surface. In addition, lack of an atmosphere and hydrosphere means that the mineral grains will not be mechanically rounded by abrasion as are most terrestrial granular soils. The increased angularity should lead

to an increase in mechanical friction. Thus, for a given porosity, the lunar soil would have a greater strength. However, if the increased angularity results in greatly increased porosity, the angle of internal friction will decrease. It cannot be predicted what the net effect will be.

It is thought (see, e.g., reference 10) that under high vacuum fine silicate powders will exhibit strong cohesive forces. If those forces exist in lunar surface materials, the lunar soils could be quite porous and yet still have a high bearing capacity.

(3) Meteor impact, micrometeorite accumulation and thermal defoliation: These three are here lumped together since they each affect grain shape, size, and total accumulation. Without going into a lengthy discussion (see, e.g., 9, 10, 11, and 12) concerning these factors, it can be said that the majority consensus of opinion is that the net material produced by these processes would be more angular than terrestrial granular soil particles, be predominantly between 1 and 100 μ in diameter (there is sharp disagreement concerning size distribution), and form a soil of the order of several centimeters to meters in depth. It must be emphasized, however, that the nature of the lunar soil is not determined by a majority consensus of opinion.

(4) Radiation: The possible effects of radiation are manifold and have been well reviewed by Ryan.[9] He concluded that radiation could act as an important soil accretion mechanism. Wehner[13] proposed that sputtering processes could cement an initially loose, porous lunar soil and that the proton bombardment could result in chemical changes such that the lunar surface is covered with metals and/or metal oxides.

VI. DISCUSSION OF ESTIMATES OF BEARING CAPACITY OF LUNAR COHESIONLESS SOILS

Although one cannot accurately predict what the porosity of a lunar cohesionless soil will be, since the individual factors cannot be evaluated, Winterkorn[14] has made a rough estimate of the bearing capacity of a hypothetical 50% porosity lunar soil assuming that the angle of internal friction is = 26.5 degrees (Tan ϕ = 0.5). This estimate is 5.45 r grams/cm^3 where r is the radius in cm of the loaded area. For a 50 cm radius pad, this is about 4 psi. Critical

to the computation, as noted in III, is the value of the angle of internal friction. Dry terrestrial sands have widely varying angles of internal friction, some of which are shown below.[2]

	Round Grains Uniform	Angular Grains Well Graded
Loose	28.5°	34°
Dense	35°	46°

It is obvious that the angle of internal friction increases as density and angularity increase. If a potential lunar granular soil is indeed highly porous with rounded grains, Winterkorn's upper estimate of 26.5° is not apt to be far off if the coefficient of friction is similar to that of terrestrial soil materials. However, if the coefficient of friction is higher (mineral grains exposed to the atmosphere usually have $f \sim 0.2$), say 1, as may be possible in lunar vacuum,[9] the angle of internal friction will be higher for a given porosity.

VII. DISCUSSION OF ESTIMATES OF BEARING CAPACITY OF LUNAR COHESIVE SOIL

Cohesive in lunar soils will in all probability result from direct bonding or cementation between grains. Most soil engineers believe that if strong cohesive forces are present lunar soils may be very porous. Numerical estimates, however, of the porosity of lunar soils are hard to come by although Hapke and Van Horn[15] conclude that the lunar surface must be covered with an optically thick ($\sim$ 1 mm) layer of "dust" of 90% porosity. Whether such a high porosity could continue for any significant depth is unknown. Hapke and Van Horn noted that the highly porous structure which they built up by air-sifting of small particles (micron size) begins to collapse at about 1 cm depth. They then contend that on the moon the highly porous layer might be as thick as 60 cm. A layer of "dust" with a porosity of about 90% necessitates, they claim, small particles of average diameter about 10 microns and strong cohesive forces between particles. Accordingly, Winterkorn[14] and Scott[16] have constructed models of lunar cohesive soils based on those properties.

Winterkorn has used three approaches in estimating the bearing strength of a "fairy castle" structure composed of 10 micron spheres in an isotropic array with porosity of 90%. The bonding energy was assumed to be 5 kcal per mole bonds

which is the energy of the dipole-dipole interaction of water molecules. It is a very conservative estimate since a silicon-oxygen bond, the kind to be expected in much of the bonding in silicate minerals, has an energy of 90 kcal/mole. In the calculations of shear strength the strength is directly proportional to the assumed bond energy. It becomes obvious, however, that the assumed bond energy is probably the least critical of all the assumptions made.

In the first approach it was assumed that there was only 1 bond/particle in the shear plane and that the bond length was 3A. This led to a shear strength of 3.92×10^{-6} kg/cm^2. As noted by Winterkorn, this value is probably too low because there will be more than 1 bond per particle. It is not possible to estimate that quantity even as to order of magnitude.

The second approach assumed that the solid phase material has the same shear strength as granite ($\sim$ 190 kg/cm^2) and leads to a shear strength of 41 kg/cm^2.

Winterkorn's third approach makes use of the fact that the surface energy of freshly sheared surfaces is about 1000 ergs/cm^2, leading to a calculated shear strength of 1.47×10^4 kg/cm^2.

Winterkorn concludes that an overall conservative estimate of the shearing strength of lunar soil is 10 kg/cm^2 which corresponds to a bearing capacity of 62.8 kg/cm^2. He also feels that such a model will furnish good traction. Any internal friction will increase the bearing capacity of a cohesive soil. As noted earlier, it is not possible to accurately estimate the angle of internal friction for a lunar soil although if Winterkorn assumes an angle of 26.5°, the bearing capacity is increased by a factor of 28.5. (The straight frictional term is negligible - the increase comes from a combined cohesive-frictional term.)

Scott[16] has taken a slightly different approach than Winterkorn, an approach which is more realistic in that Scott attempts to calculate the area of contact between grains. He does this by assuming elastic impact of spheres of various diameters (1, 10 and 100 μ) at velocities of 1, 10 and 100 cm/sec., and that the maximum area of contact at impact is the area of contact at rest. Scott also assumes a bond energy of 5 kcal/mole of bonds and 1 bond per 20A^2. He then calculates rupture stresses for porosities of 48, 74 and 86%. The model has properties such that the calculated rupture stresses are independent of particle size but depend strongly on impact velocity and porosity. Scott's calculated values

of rupture stress range from 0.7 psi (v = 1 cm/sec, n = 86%) to 240 psi (v = 100 cm/sec, n = 48%). He feels that such theoretical values may be high by as much as 10^3.

Scott has clearly recognized the problems involved in attempting to calculate soil constants, listing the following as points of difficulty:

(1) Strength of a single atomic bond
(2) Number of bonds per contact and area per contact
(3) Number of contacts per square centimeter
(4) Question of imperfections at dislocations in one contact area
(5) Mode of structure deformation - possibly more important than bond behavior
(6) Porosity of soil as a function of stress at depth
(7) Shear strength may not be developed simply as a straightforward rupture phenomenon.

It becomes quite obvious that, even if one could construct a soil with properties such as the hypothetical models, the real bearing capacity probably would not be near that calculated. To think that there is any semblance of the models to real lunar or even terrestrial soils is completely unrealistic.

VIII. CONCLUSIONS

After a brief initiation into the science of soil mechanics, certain conclusions become self-evident.

(a) Soil systems react in a complicated manner to testing. Their mechanical properties are aggregate in nature, depending upon a myriad of variables, and are relatively unpredictable a priori.

(b) Once a particular soil has been examined and tested, semi-empirical equations can be used to extrapolate certain properties, including shear strength and bearing capacity.

(c) Theory and speculation indicate that lunar soils, all else being equal, may have more strength than terrestrial soils. There is no evidence that all else is equal.

(d) Calculated values of soil constants, based on extremely simplified and unrealistic models, are not reliable and can be used only to give extreme limits which cannot be used for engineering design purposes.

PART B: SOIL MECHANICS EXPERIMENTS

The experimental aspect of lunar soil mechanics can be conveniently divided into three categories: laboratory, flight, and spacecraft.

I. LABORATORY

Vacuum Tests:

Many of the recent laboratory experiments have been concerned with performing bevameter penetration tests into "simulated" lunar soils. That simulation has been crude, at best, and has dealt primarily with evaluating the effect of vacuum on the penetration into cohesionless soils. Sjaastad[17] has reviewed much of the work done up to early 1963 and performed some vacuum shear tests. He concludes that many conflicting results reported were due to failure to control the myriad of variables present, even in sand, pumice, and glass beads, and failure to obtain and hold a good vacuum. Most vacuum tests have been performed at about 10^{-6} mm Hg, a pressure at which surfaces are probably still contaminated with gases. Performing shear tests in that vacuum and at high temperature ($\sim$ 200°C) enabled Sjaastad to obtain reasonably conclusive evidence, in accord with theory, that vacuum "clean" materials will have a higher angle of internal friction than contaminated materials. In other words, there would be an increase in penetration resistance of a lunar cohesionless soil over that of a comparable terrestrial soil.

In addition to the increased coefficient of friction in vacuum, it has been found that the cohesive forces also increase when surfaces are cleaned of contaminating gases. Hapke and Van Horn[15] have presented evidence that the lunar surface (to optical depths) must be covered by material with an extremely porous, open structure. Conceivably that "fairy castle" structure could be formed on the moon by micron-sized (1-50 μ) particles strongly bonded to each other via short-range surface forces. Hapke and Van Horn were able to create some of the postulated structure by careful air sifting of fine powders. Salisbury et al.[18] have sifted fine silicate powders in vacuum up to 10^{-10} torr and noted that the particles exhibit strong cohesive properties. They calculated a shear strength of the structure after having applied a known disruptive force. The result, 300 kg/cm^2 if atomic, short-range forces were operative, is completely unreliable since a basic

assumption involved is that the particles were 10 μ diameter elastic spheres. In all probability the particles were not sperical, were not elastic and not 10 μ in diameter (in fact, Salisbury et al. state that in all cases at least 80% of the particles were less than 3 μ in diameter).

Temperature Tests:

Halajian[10] found that the "baking" of pumice at 150°C for two weeks resulted in increased penetration resistance. It is not clear just what caused the increased resistance, and results must be termed inconclusive. Likewise, the claim by Wong et al.[19] that low temperature appears to cause a decrease in the bearing strength of pumice (at -56°F) and an increase in that of quartz sand (at -24°F) is open to question, being based on only two experiments of dubious quality.

Gravity Tests:

Halajian[8] has shown experimentally, via settling tests in liquids, that the angle of repose of cohesionless soil is essentially independent of gravity. Reduced and increased gravity experiments conducted in a plane demonstrated the correctness of the conclusions reached theoretically that sinkage of a given object in a compact, cohesionless soil is independent of gravity while the sinkage in extremely loose, cohesionless soils depends directly on the gravity.

Radiation Tests:

In sputtering experiments, Wehner[13] was able to fuse iron dust particles together by irradiating the dust with low energy mercury ions (chemically non-reactive). Subsequent experiments by Wehner et al.[20] show that solar protons and alpha particles are capable of sputtering significant material from iron and stone meteorites. The net effect is to smooth macrorelief and to roughen microrelief in addition to actually removing material. They estimate that the solar wind could cause removal of as much as 17 cm of lunar surface material over the course of 4-1/2 billion years, and could act as a cementing agent via the sputtering process. It is impossible to evaluate the relative contribution of sputtering to the overall alteration of the lunar surface.

II. FLIGHT

A. Surveyor soil mechanics instruments - landing dynamics, T.V., surface sampler and penetrometer

For any experimental program to have more than academic and speculative interest, the investigator must be conducting a realistic experiment. When a simulated model is involved, as is the case with lunar soil studies, the model has no more validity than the individual simulated properties, at best. Experiments conducted so far indicate that, all else being equal (e.g. same porosity, same grain size distribution), a lunar soil would have more strength than a terrestrial soil. However, all else is probably not equal and no present day model will enable prediction of lunar soil properties with the certainty necessary for Apollo.

It is quite obvious that the only reasonable attack is to investigate lunar soils in situ. It was the intent to do this with Surveyor by employing instruments designed to measure c, ϕ and certain other empirical constants used in sinkage and trafficability studies. Since those instruments are no longer included in early Surveyor payloads, indirect methods must be employed. Hopefully, those methods will yield data allowing the extrapolation of information for the use of Apollo.

As now envisioned, Surveyor could yield information concerning soil mechanics by four methods: landing dynamics, T.V., surface sampler and penetrometer.

Study of the landing dynamics should enable crude evaluation of surface bearing strength.[21] The information returned would distinguish among (a) hard surface with zero penetration, (b) soft surface with slight penetration and (c) very soft surface with deep penetration.

T.V. will verify and add to any conclusions drawn from landing dynamics studies by enabling direct observation of the depth of penetration of Surveyor landing gear pads and also of any skid grooves. It is probable that T.V. observation will also allow some judgment to be made concerning the degree of surface homogeneity.

Neither landing dynamics studies nor T.V. observation per se will allow determination of the soil constants which enable extrapolation from Surveyor size landing pads to LEM pads. The surface sampler should help resolve that problem. In conjunction with T.V. it can tell, via an accelerometer and scraping action, whether the surface is hard or soft and

give an indication of how hard or soft. If the surface is soft and the sampler can make a groove in the soil, a soil scientist - T.V. observer can make a judgment as to the cohesive and frictional constants for the soil, e.g. if the walls of the groove do not collapse certain limits could probably be established for the cohesion of the soil.

The penetrometer experiment (really one plate of a bevameter), if carried, will provide a point measurement of soil depth and a measure of force vs penetration. This directly augments the surface sampler. Since the soil depth affected under a loaded area is of the order of several times the footing diameter (2) it is highly desirable to sample or test to at least 2 ft. (Surveyor pad diameter is about 12"). If the soil is incompetent, relative to the penetrometer, a measure of depth or minimum depth is obtained. If the soil is competent, an empirical measure of its strength is obtained. Extensive terrestrial testing of the penetrometer should be done for calibration purposes - this, then, would allow some limiting values to be placed on the lunar soil strength.

B. Follow-on Experiments

Terrestrial soils are notoriously inhomogeneous, i.e., correlation distances are extremely small and testing is done on a small grid. Although T.V. observation will allow some judgment to be made as to the degree of surface homogeneity, it will tell nothing about subsurface conditions. Presently there are four types of instruments available which could conceivably be used for statistical evaluation of lunar soil conditions: the bevameter, lunar roving vehicles, accelerometers, and penetrometers.

(1) Bevameter: Assuming that a flight-worthy instrument could be built, we must consider the possible returns. In Part A, it was shown that a single bevameter test per se is not reliable for extrapolative purposes. Multiple measurements [see (2)] are needed over a large area for at least two reasons: one, the chance of a given measurement being reliable is small and, two, the area accessible to a Surveyor-attached instrument may be highly disturbed during touchdown and thus not be representative of the fresh lunar surface.

A single bevameter measurement might be useful if used in conjunction with other experiments. For instance, if it can be ascertained by other means that the lunar surface is homogeneous, then the bevameter quantitative data would enable the establishment of reasonable limits for the soil constants.

(2) Lunar Roving Vehicles: Multiple bevameter-type measurements made from a small lunar roving vehicle could be valuable in determining pressure vs sinkage characteristics of the surface. It would be desirable to use as large plates as possible in order to extrapolate results to sinkage of LEM-size pads. I do not know how applicable such results would be for studies concerning large lunar rovers (1000's of pounds) although as a first guess it would seem that the best information for such considerations would come from observations of the small rover itself, i.e., the small rover would provide a scale model test of a large rover. Obviously, T.V. coverage would be a necessary complement to lunar surface testing from a roving vehicle.

(3) Accelerometers: The use of small impact accelerometers would allow remote sampling of the lunar surface. McCarty and Carden[22] have started a thorough study of impact characteristics of accelerometers on various materials. They distinguish three types of impact - elastic, plastic, and penetration - characterizing each by specific pulse shape, magnitude of peak acceleration, rise time, and pulse duration. They believe that they can establish an empirical penetration or hardness scale which would be valid for remote lunar testing. It would also be possible in many cases to distinguish layering phenomena. Used in combination with the accelerometer experiments connected with the surface sampler, the spherical, omni-directional accelerometers such as developed by Ford Motor Company[23] could be invaluable in correlating and testing large areas of the lunar surface. According to Hechtl[24] it may be possible, though not yet demonstrated, that a semi-empirical relationship between acceleration results and soil constants can be established.

(4) Penetrometers: The use of cone penetrometers as remote soil testing instruments does not appear very useful. Their non-symmetrical geometry would demand rather elaborate guidance control and information return relative to accelerometers if quantitative information were required. Modern terrestrial aerial penetrometers[25] are strictly go - no - go types which would require considerable modification in order to be capable of returning useful information. In all likelihood, changes would be in the direction of accelerometers which are already well into the development stage.

C. Spacecraft Tests

It is desirable that Surveyors land on the moon many times before the LEM lands. It is imperative that the best possible use be made of information obtained from such landings. Rather than be forced to rely upon vague static

scaling laws, dependent only on soil properties, a body of empirical knowledge should be built up based on static and dynamic testing of Surveyor and LEM spacecraft on many kinds of surfaces. In turn, this data should be correlated with accelerometer experiments. A sufficient store of knowledge should be available such that after a Surveyor landing the question "could the LEM have landed on the same surface?" could be answered.

Terrestrial testing must be realistic; otherwise it has little significance. This should not be construed as a recommendation favoring the simulation of lunar soils but only as one suggesting that the use of representative natural terrestrial soils and pulverized rock might give more meaningful results than the use of materials such as wood shavings. Hughes Aircraft Company[26] found, for example, that shavings were suitable for static Surveyor tests but that they exhibited considerable spring action during dynamic testing.

For a more comprehensive analysis of the desirability of conducting meaningful lunar landing dynamics studies, the reader is referred to the paper by Powers.[27]

III. CONCLUSIONS

(a) As far as Apollo is concerned, laboratory simulation of so-called lunar soils and the testing thereof is relatively wasteful of time, effort, and money. The simulation is so crude and there are so many unknown variables involved in determining the mechanical behavior and physical make-up of soils that it would be extremely fortuitous if a realistic model were ever made. No engineering design can be based on the behavior of simulated lunar soils and it is doubtful whether further terrestrial testing of such soils as has been done will aid much in the interpretation of Surveyor experiments.

(b) Surveyor and related lunar experiments hold the best hope for determining lunar soil characteristics. Accelerometer experiments and/or soil mechanics tests from a roving vehicle should be capable of large area sampling and allow terrestrial observors to arrive at a confident judgment as to the type of and degree of homogeneity of the lunar surface.

(c) On account of the difficulty involved in understanding and predicting the behavior of spacecraft landing systems, it is desirable to undertake an active program of

static and dynamic testing of Surveyor and LEM landing systems. The aim of this is to establish empirical correlation and scaling relationships between the two systems. In turn, this may eliminate much of the need to rely upon soil scaling laws which demand relatively precise knowledge of soil "constants" and which do not allow for differences in alnding dynamics between the Surveyor and LEM systems.

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